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System Engineering Report

Thermal Control of Nasmyth Tube Walls

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Prep by: Dan Machak	**Date:** 9/14/90	**Report No:** DM-NAS01
Subject: Thermal Control of Nasmyth Tube Walls	**Project:** SOFIA	

Introduction

The thermal control of the Nasmyth tube is a sensitive issue with regard to the quality of the infrared image reaching the scientific instrument. Experience has shown that even a small temperature increase of a surface near the optical path can affect the resulting image. The current requirement is that no surface in the cavity shall be hotter than 2° K over the ambient cavity air temperature. This report focuses mainly on the design concept presented in the Zeiss phase B final report, which includes air flow through channels around the perimeter of the inner wall of the Nasmyth tube. A cutaway view of the Nasmyth tube and a blowup of the Nasmyth wall is shown in Figure 1.

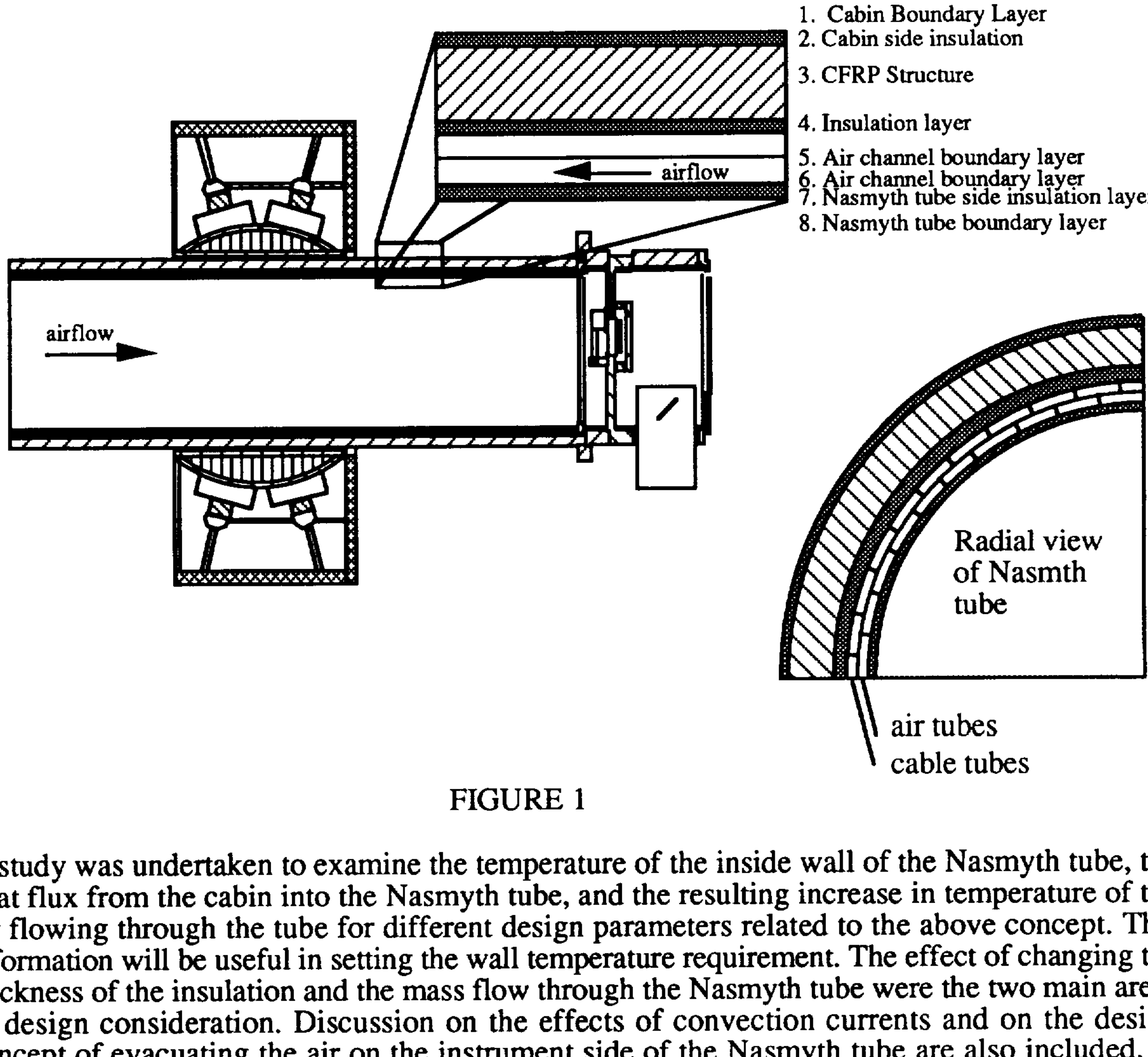

FIGURE 1

A study was undertaken to examine the temperature of the inside wall of the Nasmyth tube, the heat flux from the cabin into the Nasmyth tube, and the resulting increase in temperature of the air flowing through the tube for different design parameters related to the above concept. This information will be useful in setting the wall temperature requirement. The effect of changing the thickness of the insulation and the mass flow through the Nasmyth tube were the two main areas of design consideration. Discussion on the effects of convection currents and on the design concept of evacuating the air on the instrument side of the Nasmyth tube are also included, as well as areas of further consideration and related thermal issues.

Assumptions of study

1. Only heat transfer due to conduction and convection were considered. The effect of mass leaks and heat transfer due to radiation were not considered.
2. Heat transfer along the radial air channel walls was neglected.
3. For purposes of calculating the Nasmyth wall temperature, the scientific instrument mounting flange is assumed to be perfectly insulated.
4. The study was done for a steady state; no cooldown effects were included.

Summary

Referring to Figure 1, the current design of the Nasmyth tube, from the phase B final report, has no insulation in layers 2 and 7 and 1 cm of insulation in layer 4. Along with a mass flow of approximately .10 kg/s, this makes the Nasmyth wall temperature fall in the range of 4° to 7° K hotter than the ambient air temperature. Various design options were studied to determine whether this temperature difference could be reduced without any radical design modifications. The following conclusions were reached:

1. By increasing the insulation in layer 4 to 3 cm, which is the maximum thickness which still gives the minimum Nasmyth tube inner diameter of 76 cm, the wall temperature difference was in the range of 2° to 3.5° K.
2. By combining the increase in insulation with an increase in mass flow of 50%, the wall temperature difference is decreased to 1.5° to 2.5° K.
3. By tapering the Nasmyth insulation tube, it is possible to get an increased amount of insulation on the cabin end of the Nasmyth tube and therefore decrease the wall temperature difference into the 1° to 1.5° K range.
4. Putting insulation on the inside of the Nasmyth tube in layer 7 is not as effective as putting it in layer 4.
5. To cool the instrument mount area to acceptable levels, a large increase in total mass flow is necessary. Further study is needed in this area to come up with a workable design.

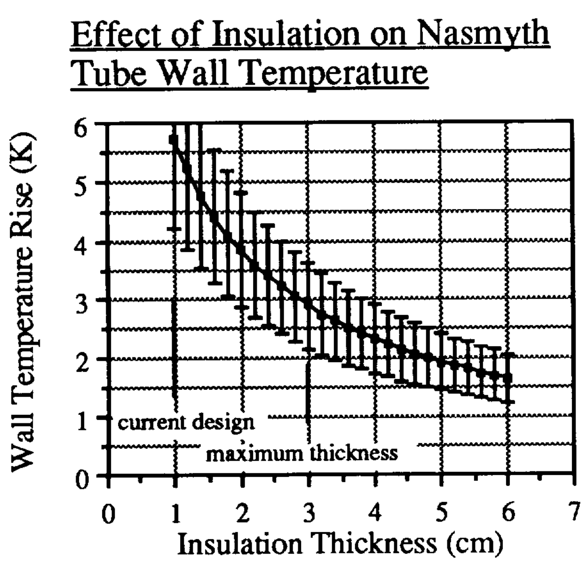

FIGURE 2

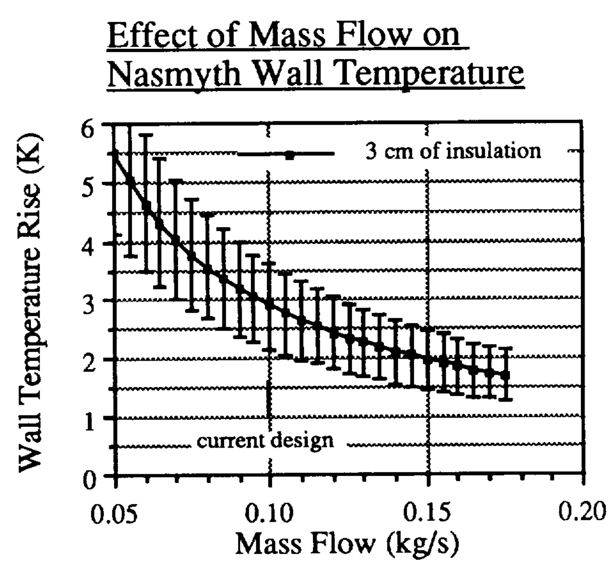

FIGURE 3

Design Considerations

CURRENT DESIGN

The two main parameters that affect the rate of heat transfer and the resulting temperature rise of the wall are the amount of insulation and the mass flow rate through the system. Figures 2 & 3 show the dependance of the wall temperature upon these two parameters. Referring to Figure 1, layers 2,4, and 7 in the Nasmyth tube all correspond to different layers of insulation. For this analysis, layers 1 and 4 are equivalent since layer 3, the CFRP structure has a relatively high conductance. Therefore in the graph, outer insulation thickness refers to the combined thickness of layers 1 and

4. In these graphs, there is no inner insulation, which corresponds to layer 7 in Figure 1. From here on, d_i will refer to the insulation thickness of layer *i*. The current design as presented in the Zeiss phase B final report has $d_2 = 0$ cm, $d_4 = 1$ cm, $d_7 = 0$ cm, and a mass flow of 0.1 kg/s.

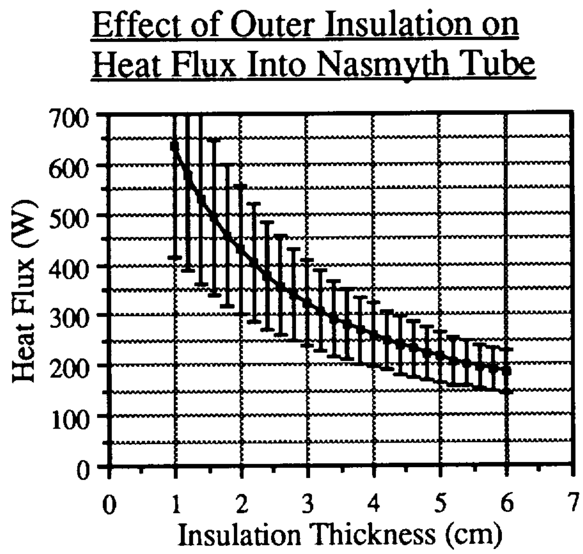

FIGURE 4

From Figures 2 & 4, this corresponds to a heat flux between 400 and 900 Watts and a resulting temperature rise of the Nasmyth Tube wall of 4.25° to 7.25° K over the ambient air temperature. Due to the drive mechanisms and other equipment on the cabin side of the Nasmyth Tube, there may not be enough room to put insulation on this part of the Nasmyth Tube. For this reason, the current design has all the outer insulation in layer 4. If this layer is increased to 3 cm thickness, then the inner diameter of the Nasmyth tube would be reduced to 76 cm which is the minimum diameter currently required. This would correspond to a wall temperature increase of 2° to 3.5° K over the ambient cavity temperature. If in addition to the 3 cm of insulation in the tube, it is possible to get another 3 cm of insulation on the outside of the tube (cabin side), then the increase in the wall temperature would fall in the range of 1.25° to 2° K, which would meet the current requirement.

There is still uncertainty, however, whether the 2° requirement is strict enough. Experience has shown that smaller temperature differences near the beam path have affected the infrared image. Therefore, even if it is possible to use 6 cm of insulation in the Nasmyth tube, it may still be desirable to investigate other designs that could give a lower temperature difference on the wall.

TAPERED INSULATION TUBE

One possible way to use more insulation where it is needed most is to use a tapered insulation tube as shown in Figure 5. The minimum diameter of 76 cm for the inside of the Nasmyth tube is critical only at the cavity end of the Nasmyth tube. As the beam travels towards the cabin side of the tube, there is more space between the beam and the Nasmyth tube walls that could be used for insulation. This allows the possibility to use a thicker insulation layer on the cabin side of the Nasmyth tube where the heat flux is high, and then taper down the insulation tube on the cavity side where the need for insulation is not critical. The extra insulation would be the most effective on the outer layer d_4. Up to 8 cm of insulation could be used with this concept, which would lead to a wall temperature of about 1° to 1.5° K above the ambient temperature.

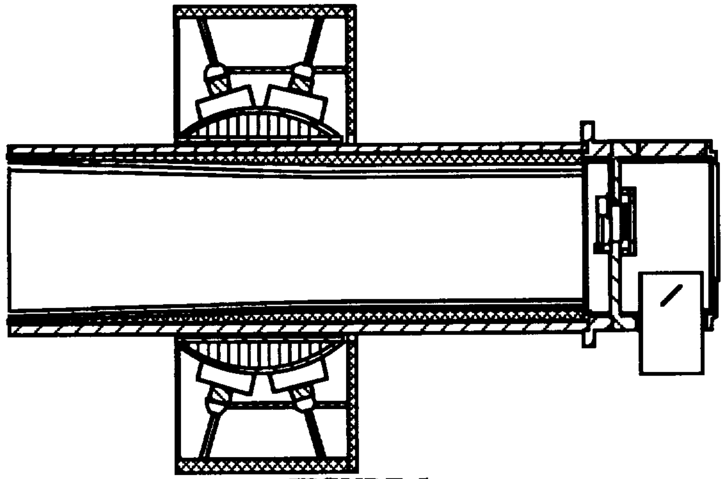

FIGURE 5

DISTRIBUTION OF INSULATION

A study was done to determine, given a certain amount of insulation that can be used in either layers 4 or 7, what would be the most effective way to distribute the insulation so as to obtain the lowest temperature increase of the Nasmyth wall. Figures 6 & 7 show the increase in the air flowing through the channel and the increase in the wall temperature as a function of the thickness of the inner insulation layer, d_7. Each curve represents a total amount of insulation and is plotted against the amount of that insulation applied to layer 7. It can be seen that for having an optimal distribution of insulation between layers 4 and 7, the wall temperature is not more that .5° K cooler than just having all the insulation put in layer 4.

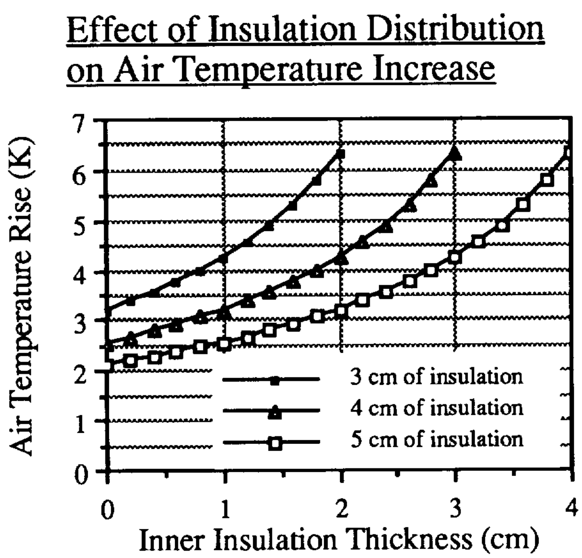

FIGURE 6

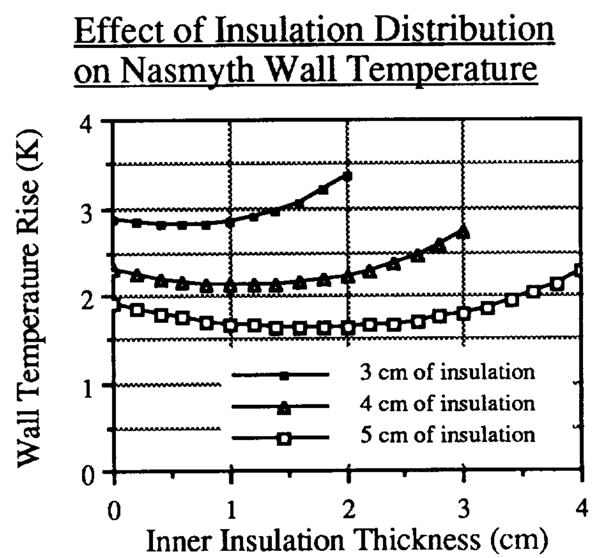

FIGURE 7

For the added complexity, it would not be worth having an extra insulation layer for this small gain. Another problem with insulation in layer 7 is that the insulation would have to be applied uniformly along the whole length of the Nasmyth tube. Since insulation applied to layer 7 does not prevent any heat flux from the cabin into the air channel, the air temperature in the channel is increased accordingly. Therefore, if insulation in layer 7 is applied only along the cabin end of the Nasmyth tube, the air that is heated up in the channel will then heat up the wall on the cavity end of the Nasmyth tube. Conversely, insulation may effectively be used on the cabin end alone in layer 4 and since there is no heat input into the air channel on the cavity end of the Nasmyth tube, the air in the channel will heat the wall with a fairly constant distribution.

COOLING OF THE NASMYTH TUBE/SCIENTIFIC INSTRUMENT INTERFACE

A problem can arise in the section aft of the pressure window. The air in this area is not circulated with the air channel in the Nasmyth tube and is therefore sensitive to heating and convection currents which can affect the seeing. A proposed design to alleviate this problem is to connect the scientific instrument and the pressure window with a tube as shown in Figure 8.

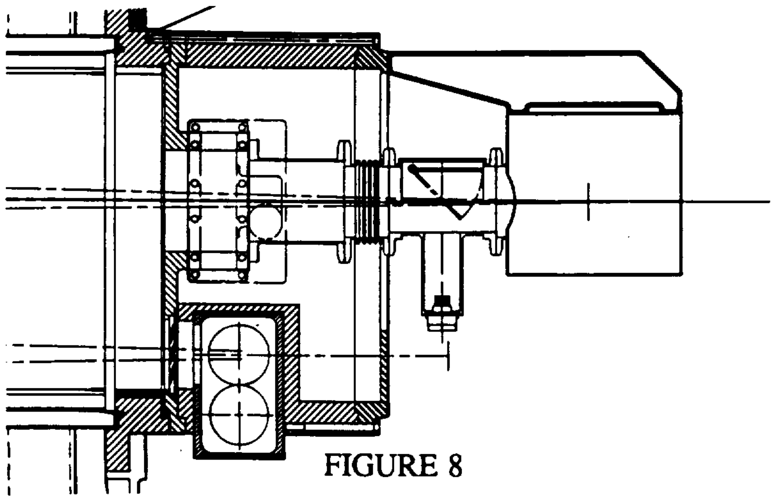

FIGURE 8

This tube can then have a hose attached which will pull air through the tube or pull a vacuum in the tube. The hose could either be attached to a vacuum pump or could lead to a low pressure area on the airplane skin. A preliminary study shows that pulling air through the tube at about .08 kg/s (9 m/s) and 8 cm of insulation would result in a wall temperature increase of approximately 2° K. The details of how to achieve the flow through the tube in this area will be examined in an upcoming study.

Analysis

Referring to Figure 1, the air flows in from the left and continues through the air channels as indicated by the arrows. What happens is that heat flows into the Nasmyth tube through the end that extends into the cabin. Most of this heat is then carried away by the flow through the air channel. Heat is then transferred from the air channel to the inside of the Nasmyth tube, and the inner wall is heated up. The methodology is to use the incoming heat flow to calculate the total temperature rise of the air flowing through the air channel. The step by step process is described below.

In order to calculate the heat flow into the Nasmyth tube, it is necessary to first find out the total conductance across the layers of the Nasmyth tube, k_t.

$$k_t = \left(\sum_{i=1}^{5} \frac{1}{k_i} \right)^{-1} \qquad \text{units: } \frac{W}{m^2 K}$$

Now we can calculate Q:

$$Q = k_t A (T_{cab} - T_{cav})$$

where A is the circumferential area of that part of the Nasmyth Tube that is sticking out into the cabin. Once we have Q, we can calculate the average temperature rise of the air flowing through the air channel. Using a control volume approach, we can do an energy balance of the air flowing through the Nasmyth tube.

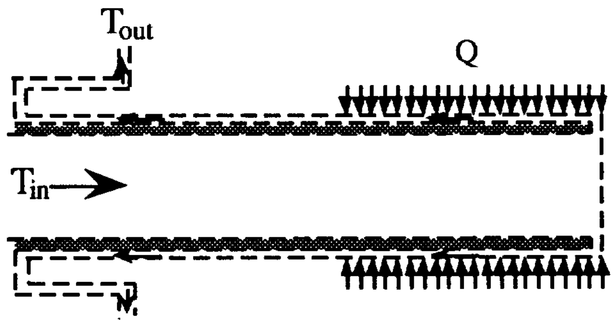

FIGURE 9

The total temperature rise of the air is calculated from the following:

$$\Delta T = T_{out} - T_{in} = \frac{Q}{\dot{m}C_p}$$

Where $\dot{m}$ is the mass flow through the Nasmyth tube in kg/s and C_p is the specific heat of air in J/kgK. From this equation we can calculate the temperature of the air leaving the control volume. For this analysis, the air temperature in the air channel is assumed to be constant and equal to T_{out}. What actually happens is that the air will heat up to a little above T_{out} in the air channel, just past the cabin side of the Nasmyth tube, and will lose just enough heat along the rest of the Nasmyth tube to bring it back down to T_{out}. However, for getting a value for the maximum wall temperature, this is a very good approximation. The temperature difference of the inside wall of the Nasmyth tube can now be calculated. The heat flux from the air channel to the Nasmyth tube is calculated from:

$$Q_w = k_w A(T_{out} - T_{in})$$

where

$$k_w = \left(\sum_{i=6}^{8} \frac{1}{k_i} \right)^{-1}$$

The temperature difference of the wall is equivalent to the temperature drop across the thermal boundary layer of the Nasmyth tube and can be calculated from:

$$T_w = T_{in} + \frac{Q_w}{k_8 A}$$

Appendix A: Parameters

Following is a list of the parameters used in the study along with their uncertainties.

Cavity temperature:	230° ± 5° K	Stagnation temperature
Cabin temperature:	295° ± 2° K	Room temperature
Nasmyth tube cavity side wall surface area:	5.7 ± .25 m^2	Zeiss phase B final report
Nasmyth tube inner diameter:	.76 m	Zeiss phase B final report
Nasmyth tube length:	2.3 m	Zeiss phase B final report
Mass flow	.1000 kg/s	Zeiss phase B final report
Insulation conductivity:	.035 ± .0025 W/(m-K)	Zeiss phase B final report
Air conductivity:	.0215 ± .0004 W/(m-K)	Standard Atmospheric tables FL410
Air density:	.290 ± .02 kg/m^3	Standard Atmospheric tables FL410
Air viscosity:	(1.55 ± .025) x 10^{-5} kg/(m-s)	Standard Atmospheric tables FL410

Air specific heat: 1005.0 ± .1 J/(kg-K) Standard Atmospheric tables FL410

Appendix B: Calculation of convective heat transfer coefficients

The convective heat transfer coefficients for the boundary layers on the inside of the Nasmyth tube and in the air channel were calculated using empirical formulas based on experimentation.

The heat transfer coefficient for the boundary layer inside the Nasmyth tube was calculated using the following formula: (Taken from the Zeiss Phase B final report; 4.2.1.0.4 - 10)

$$k_8 = \frac{Nu\ \kappa_{air}}{D}$$

where

$$Nu = \frac{\frac{\xi}{8}(Re - 1000)Pr}{1+12.2\sqrt{\frac{\xi}{8}}\ (Pr^{2/3} - 1)}\left(1 + \left[\frac{D}{L}\right]^{2/3}\right)$$

and

$$\xi = [1.82 \log_{10}(Re) - 1.64]^{-2}$$

For the boundary layers inside the air channel, the following equation was used. (Taken from "Heat Transmission" by William McAdams, p242-243.)

$$k_5 = k_6 = \frac{.023\rho C_p V}{Re^{.2}\ Pr^{.667}}$$

Appendix B Error Analysis

The uncertainties in the analysis arise from lack of knowledge about the given parameters. The following equations show how the uncertainty in the wall temperature and heat flux were calculated.

$$d\Delta T_w = \Delta T_w\left[\left(\frac{.8k_{ch}}{k_5} + \frac{.8k_w}{k_6} - 1\right)\frac{d\rho}{\rho} + \left(\frac{k_w}{k_7} + \frac{k_{ch}}{k_2} + \frac{k_{ch}}{k_4}\right)\frac{d\kappa_i}{\kappa_i} + \left(\frac{k_w}{k_8} - 1\right)\frac{dk_8}{k_8} + \left(\frac{k_{ch}}{k_1} - 1\right)\frac{dk_1}{k_1} + \frac{dA}{A} + \frac{(dT_{cab} + dT_{cav})}{(T_{cab} - T_{cav})}\right]$$

$$dQ = Q\left(\frac{dk_t}{k_t} + \frac{dA}{A} + \frac{(dT_{cab} + dT_{cav})}{(T_{cab} - T_{cav})}\right)$$

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System Engineering Report

Approved By:	
Subject: Thermal Control of Nasmyth Tube Walls - Warm Air Bearing Study	**Project:** SOFIA

Prep by: Dan Machak	**Date:** 6/17/91	**Report No:** DM-005

This SER will serve as an appendix to SER DM-001 (9/14/90). In the original study, the temperature of the wall of the Nasmyth tube was studied while assuming that the air bearing had been cooled to the temperature of the ambient cavity air at mission altitude. The study in this appendix compares the cold air bearing case just described, and the case where the air bearing is at the temperature of the cabin air, which will be called the warm air bearing case. The thermal boundary for these two cases are shown in figures D-1 and D-2 below. This study was done to aid in evaluating the possibility of moving the thermal barrier separating the cabin and cavity so that the air bearing is included on the warm side of the barrier. This change would reduce the complexity of the air bearing system.

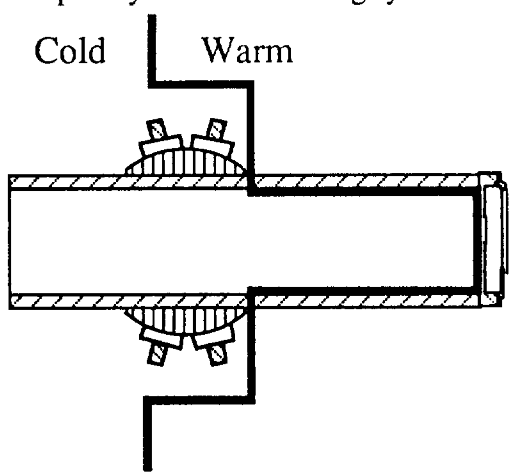

Figure D-1 Cold Air Bearing

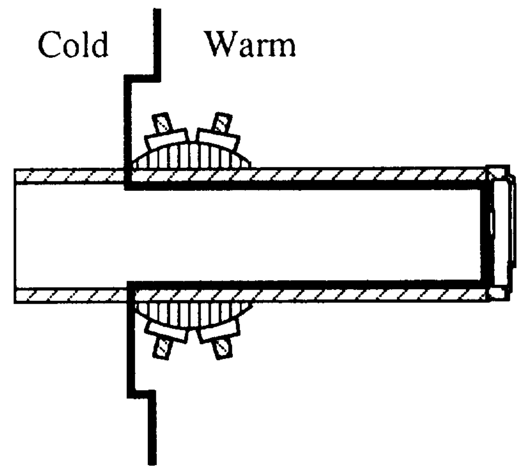

Figure D-2 Warm Air Bearing

Following the analysis given in SER DM-001, the equations were reduced to obtain the dependance of the difference in wall temperature above that of the ambient air as a function of the surface area of the Nasmyth tube. As in the original analysis, the instrument end of the Nasmyth tube is assumed to be perfectly insulated, with the only heat flux coming from the sides of the Nasmyth tube. All parameters are the same as is given in SER DM-001 except for the surface area. Since the air bearing is a large thermal mass and will not undergo pre-cooling for the warm case, the analysis assumes the air bearing to remain at the cabin temperature. The area of the thermal boundary is 5.7 m^2 for the cold air bearing case, and 8.8 m^2 for the warm air bearing case.

For comparison, figures D-3 and D-4 show plots of insulation thickness vs. mass flow for different lines of constant wall temperature increase for the cold and warm air bearing cases respectively. Insulation thickness and mass flow are the two main parameters involved in the thermal design of the Nasmyth tube. Also plotted in figure D-5 is the correlation between the cold and warm air bearing cases. For a given set of insulation thickness and mass flow, the wall temperature for the warm air bearing case is plotted against the wall temperature for the cold air bearing case. This shows the effect of moving the thermal boundary to include the air bearing on the cabin side. This plot shows that the warm air bearing will result in wall temperature increases approximately 50% higher than those of the cold air bearing case, if other variables are kept constant.

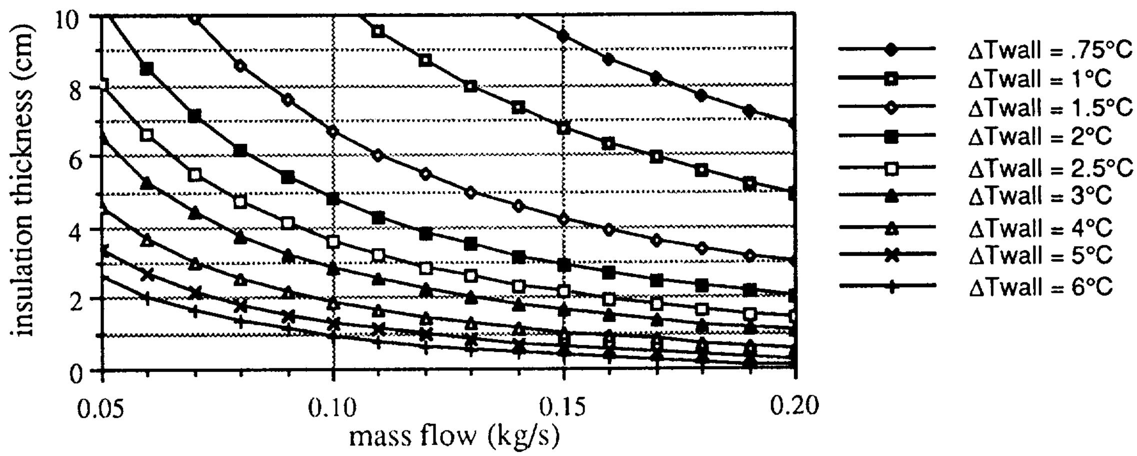

Figure D-3 Cold Air Bearing Case

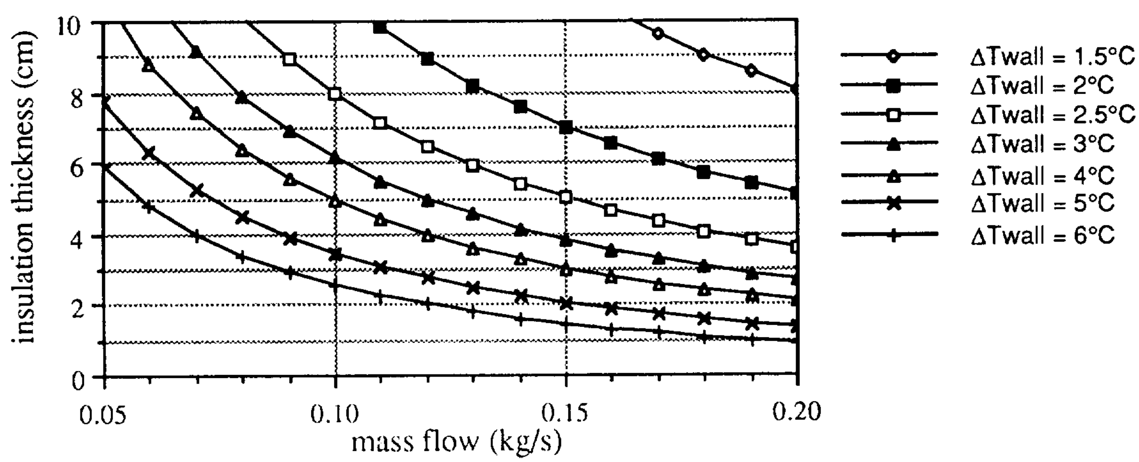

Figure D-4 Warm Air Bearing

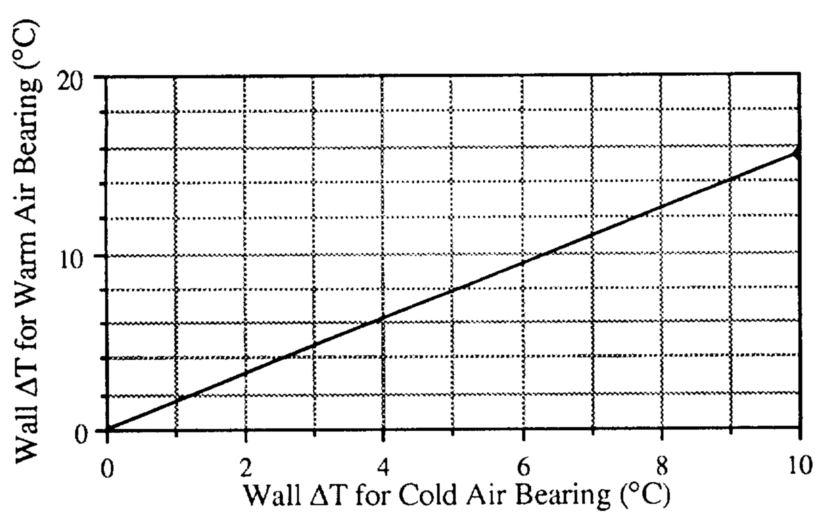

Figure D-5 Warm Air Bearing VS. Cold Air Bearing Wall Temperature Increase